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## Development of a Differential Settlement Model for Design and Maintenance of Track Transitions

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### SUMMARY

Differential Settlement is a key factor in the performance of track transitions, such as bridge approaches, highway/rail intersections (road crossings), and diamond crossings. Under sponsorship from the Association of American Railroads, Transportation Technology Center, Inc. (TTCI) developed a tool for predicting differential settlement of track at these transitions. This *Technology Digest* describes the capabilities of the model and provides an example of how the model can be used to develop track transition designs that will be more stable than those used today.

Features of the model include:

- Prediction of track settlement for two track structure configurations (bridge and approach)
- Prediction of differential settlement; one side relative to the other
- Allowance for new construction and track raises
- Track characteristic inputs (qualitative measures of track or specific values of geotechnical measures)

Reduction of subgrade stresses on the softer side of the transition is essential for developing a stable track transition with acceptable differential settlement rates. Subgrade stress reduction can be accomplished in several ways. These include:

- Lowering static or dynamic loads – lowering dynamic loads may be possible with better track surfacing or improved car components
- Using stronger materials
  - Ballast
- Crossties
  - Composites
  - Closer spacing
  - Wider footprint
  - Continuous rail support (e.g., longitudinal ties)
- Platework: multi-tie plates
- Rail: larger section rail and additional rails as track stiffeners

The results of this project would not have been possible without the synergies developed from Federal Railroad Administration sponsored work.

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**DIFFERENTIAL SETTLEMENT MODELING**

Differential settlement is a key factor in the performance of track transitions, such as bridge/approaches, highway/rail intersections (road crossings), and diamond crossings. The relative amount of track settlement caused by the ballast and subgrade substructure layers can be determined with the Association of American Railroads’ ballast and subgrade deformation models. These models have been developed from field data of track substructure deformation and laboratory test data.

**BALLAST LAYER DEFORMATION MODEL**

The ballast deformation model was developed to predict the timing of required tamping maintenance and ballast renewal at the end of ballast life.<sup>1</sup> The ballast settlement equation was derived from laboratory and field measurements using instrumentation that measured ballast displacement in the track structure with cumulative loading.

Equation 1 determines the basic form of the ballast settlement:

$$\epsilon_p = \epsilon_1 * (N^b) / 100\% \tag{1}$$

Where  $\epsilon_p$  is the permanent ballast strain,  $\epsilon_1$  is the plastic strain occurring with the first load cycle, N is the number of repeated load cycles on the ballast and b is a constant exponent found from analysis of field data. Typical nominal values for  $\epsilon_1$  and b parameters are 0.22 and 0.21 percent, respectively. The N value is derived from the design wheel load, P, and the number of axle loads which cause a load cycle on the ballast.

Using the ballast strain equation, the ballast settlement  $\partial_p$  in 1 year following construction, assuming a 12-inch-thick ballast layer and 75 million gross tons (MGT) of traffic:

$$\partial_p = 0.22 * (2,272,727)^{0.21} (12 / 100\%) = 0.57inches \tag{2}$$

Assuming that the ballast has been in place for many years and that the upper 6 inches of ballast has been disturbed by tamping, the ballast settlement 1 year after tamping is:

$$\partial_p = 0.22 * (2,272,727)^{0.21} (6 / 100\%) = 0.29inches \tag{3}$$

The ballast settlement values in Equation 3 are for nominal conditions of ballast material quality, amount of ballast fouling, wheel load magnitude, and other parameters. The model applies internal corrections which increase or decrease the nominal ballast settlement based on the actual value of these parameters as input by the user. The rate of ballast deformation calculated by the model will be used together with the subgrade deformation rate to show how much each component contributes to total track settlement.

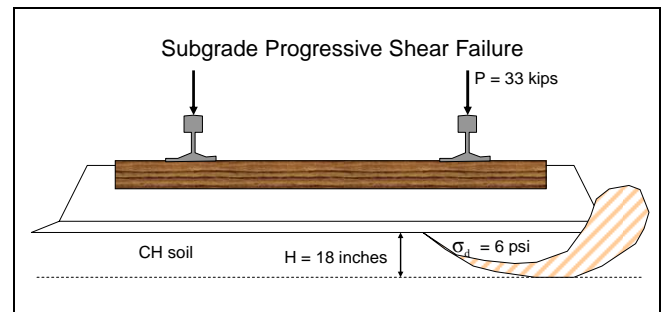
**SUBGRADE LAYER DEFORMATION MODEL**

The subgrade deformation model developed by Li uses the soil plastic strain equation:<sup>2</sup>

$$\epsilon_p = a(\sigma_d / \sigma_s)^m * (N^b) / 100\% \tag{4}$$

Where a, m, and b are parameters pertaining to soil type,  $\sigma_d$  is the soil deviator stress (maximum principal stress minus the minor principal stress),  $\sigma_s$  is the soil unconfined compressive strength, and N is the number of repeated load cycles on the subgrade.

The subgrade model assumes the nature of subgrade failure under loading is a progressive shear at the surface with soil strain developed over the top 6 to 18 inches of the subgrade layer. A progressive shear failure is shown in Figure 1 with its characteristic sideways and upwards squeezing of soil. Measurements of near surface subgrade stresses, where this type of bearing capacity failure has formed, show that the largest deviator stresses in the soil driving this movement are located between the rail-tie intersection and the tie end.<sup>3</sup> Visual inspection of the subgrade failure surface confirms that this is the location where failure starts and has the deepest depression.



**Figure 1. Example Case for a Subgrade Progressive Shear Failure**

For an assumed soft clayey soil type (CH soil) that will form a progressive shear failure over the top 18 inches of subgrade, with an unconfined soil strength of 10 pounds per square inch (psi) and annual tonnage of 75 MGT, the subgrade settlement rate will be calculated using Equation 4. The soil deviator stress for the near surface subgrade should be determined using an analysis method such as the GeoTrack™ model, although a conservative assumption for  $\sigma_d$  for these conditions is 6 psi providing a stress/strength ratio ( $\sigma_d / \sigma_s$ ) of 0.6.<sup>4</sup> This is conservative because for an in-track test with otherwise similar conditions, a lower subgrade stress ratio of 0.5 was measured with a greater 39,000-pound wheel loading than assumed in Figure 1.<sup>3</sup>

The repeated load N representing the number of axle load cycles per year is calculated as:

$$N = 75MGT * (2,000,000kips / MGT) (4wheels / cycle * P) = 75 * (500,000) / 33 = 1,136,363 \tag{5}$$

As mentioned for ballast, it is conservatively assumed that one axle corresponds to one load pulse even though there is only partial unloading of vertical ballast stress between axles of a truck. However, at the subgrade depth, the load from two axles (or four wheels as in the equation above) typically merges into one load pulse with little or no unloading between them, so the N for the subgrade is half that for the ballast. Finally, the a, m, and b parameters for CH soil are 1.2, 2.4, and 0.18, respectively:<sup>2</sup>

$$\partial_p = (H) * a(\sigma_{d1} / \sigma_s)^m * (N^b) = (18)1.2(6 / 10)^{2.4} (1,136,363)^{0.18} / 100\% = 0.78inches \tag{6}$$

Or a soil deformation for 1 year of 0.78 inch for newly constructed subgrade. This large initial settlement is characteristic of a subgrade that has been compacted during

construction, but not yet experienced traffic loading. Soil compaction removes much of the subgrade settlement, but not all. The onset of traffic loading compacts the soil further, which accounts for this initial settlement. As loading accumulates for larger N, per the relationship in Equation 6, the subgrade deformation rate becomes flatter with settlement accumulating much slower. In fact, for subgrade that has been in place for many years, a linear rate of deformation can be assumed to apply with little error. For example, if the same assumed CH soil with a stress ratio of 0.6 has been in place many years, it has been calculated that the linear deformation strain rate is  $5.02 \times 10^{-7} * (N)$  and the resulting amount of subgrade settlement for 1 year is determined by:

$$\delta_r = (18) * 5.02 \times 10^{-7} (1,136,363) / 100\% = 0.10 \text{ inches } (7)$$

**CASE STUDY: DIFFERENTIAL SETTLEMENT AT A COAL LINE BRIDGE**

In order to demonstrate its capabilities, the Differential Settlement Model was used to predict approach and bridge settlements of a well documented case. This recently constructed bridge and approaches were examined and the model was used to explore possible track configurations that would produce less differential settlement. The Differential Settlement Model uses the output of an elastic layer model (i.e., GeoTrack™) parametric study (track modulus, ballast stress, and subgrade stresses), along with user input describing traffic, wheel load, allowed differential settlement, climate, soil properties, ballast properties, track lift during surfacing, and new or previous construction to calculate the expected settlements.

**CURRENT TRACK TRANSITION CONFIGURATION**

The first priority of the Differential Settlement Model work was to simulate the current track configuration (12 inch deep, moderately fouled approach ballast on concrete ties and 12 inch deep, moderately fouled bridge ballast on concrete ties) and verify that the results were similar to measured results from the case study site. Table 1 lists the parameters and associated values that were used to accomplish this.

**Table 1. Parameters and Associated Values Describing Current Track Configuration at Case Study Site**

MODEL PARAMETERS	
Annual MGT Tonnage	175 MGT
Inspections per Year	5
VEHICLE PARAMETERS	
Static Wheel Load	36 kips
LOCATION PARAMETERS	
Climate	Wet (25 to 50 inches precipitation per year)
Max Allowed Differential Settlement	0.6 Inch
New Construction?	Yes
Schedule for Track Maintenance*	5 Years

\*Note: Model option to schedule surfacing for non-settlement reasons, such as tie replacement.

**Table 1 (cont.). Parameters and Associated Values Describing Current Track Configuration at Case Study Site**

APPROACH PARAMETERS	
Ballast Quality	Good
Ballast Fouling Index	Moderately fouled
Ballast Thickness	12 inches
Tie Type	Concrete
Tie Spacing	24 inches
Soil Classification	CH soil
Subgrade Quality	Poor
Subgrade Depth	60 inches
Rail Weight	133 lb/yard
BRIDGE PARAMETERS	
Ballast Quality	Good
Ballast Fouling Index	Moderately fouled
Ballast Thickness	12 Inches
Tie Type	Concrete
Tie Spacing	24 Inches
Rail Weight	133 lb/yard
Tamping Raise	1 Inch

Table 2 shows a comparison of settlement results for the current track configuration. The measured settlement values were taken over a period of 70 MGT after the settlement at the site had become stable. The modeled results were taken from the initial 70 MGT of the third settlement period (after the second tamping). For example, the second tamping occurs at 385 MGT of total traffic, and the settlement values are taken from the following 70 MGT for total lifetime traffic of 455 MGT.

**Table 2. Comparison of Measured and Modeled Results for Current Track Configuration at Case Study Site**

	Measured	Modeled
MGT Since Tamping	70	70
Total MGT	Unknown	455
Number of Tampings (First 5 Years, 875 MGT)	Unknown	4
	Measured Settlement (inch)	Modeled Settlement (inch)
Approach Track	1.31	1.15
Bridge	0.74	0.76
Differential	0.57	0.39

Figure 2 shows the expected settlements and tamping cycles that would be expected at the case study, given the current conditions. Figure 2 illustrates several important points:

- Tamping is expected to be necessary at least four times over the first 5-year period (875 MGT).
- The first 35 MGT after each tamping produces a large amount of approach, bridge, and differential settlement.

- Each successive settlement period is not increasing in duration or appearing to reach any sort of settlement limit.

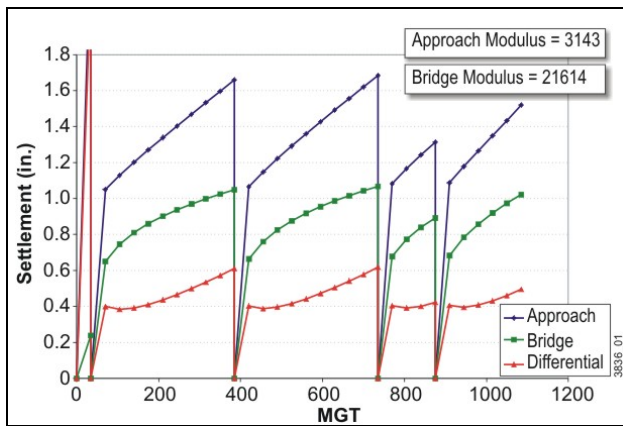


Figure 2. Expected Settlement and Tamping Cycles at Case Study Site, Given Current Site Conditions

## PARAMETRIC STUDY OF MODEL PARAMETERS

A parametric study of the model input parameters was conducted. From this study, the following parameters have the most significant effect:

- Subgrade condition
- Ballast condition (indication of fouling)
- Ballast thickness
- Crosstie properties (e.g., crosstie type)
- Wheel load

Figure 3 shows an example of a parametric study from the model. Wheel load was varied from 20 kips to 80 kips. The effect on bridge, approach track, and differential settlement is displayed for a 70 MGT period following tamping. Note that for wheel loads of the most interest (20 kips to 40 kips), settlement of the approach track increases more with wheel load than does the track on bridge. Thus, differential settlement increases with increasing wheel load.

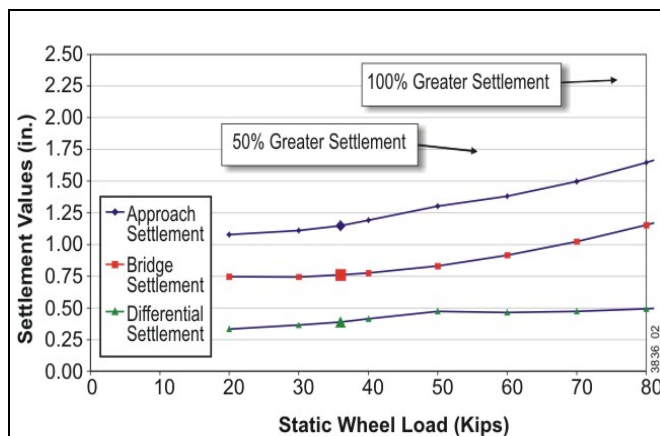


Figure 3. Use of Model as a Planning and Design Tool

Reduction of subgrade stresses on the softer side of the transition is essential to developing a stable track transition with acceptable differential settlement rates. Subgrade stress reduction can be accomplished in several ways. These include:

- Lowering static or dynamic loads – lowering dynamic loads may be possible with better track surfacing or improved car components
- Using stronger materials
  - Ballast
    - Larger thickness layers
    - Better materials
    - Tensile reinforcement (e.g., geogrid)
    - Reduced settlement gradation and particle shapes
- Crossties
  - Composites
  - Closer spacing
  - Wider footprint
  - Continuous rail support (e.g., longitudinal ties)
- Plateway: Multi-tie plates
- Rail: Larger section rail and additional rails as track stiffeners

These methods are being investigated under a companion project sponsored by the FRA to provide the most practical ways to retrofit an approach that must remain in service. Due to the constraint of keeping the line in service, preference should be given to methods that limit construction windows to perhaps 8 hours. For example, tensile reinforcement of ballast may be preferable to raising track or digging out subgrade to increase ballast layer thickness. Changing tie material may be preferable to changing tie spacing, for maintenance purposes.

## References

1. Chrismer, Steven M. February 1994. "Mechanics-Based Model to Predict Ballast-Related Maintenance Timing and Costs." PhD dissertation, University of Massachusetts, Amherst, Massachusetts.
2. Li, Dingqing, Ernest T. Selig, and Steven M. Chrismer. February 1996. "Methods for Railway Track Granular Layer Thickness Design." *Technology Digest* TD96-006. Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colorado.
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